The glueball among the light scalar mesons

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In our phenomenological analysis of the spectroscopy of light scalar mesons we do not find compelling evidence for the existence of the low mass $\kappa(900)$ or $\sigma(600)$ states nor for $f_0(1370)$ as single resonance. If the $f_0(980)$ and and $f_0(1500)$ are taken as members of the $q\bar{q}$ nonet there remains a broad object formed by $f_0(400-1200)$ and $f_0(1370)$ which is a glueball candidate $gb(1000)$.

1. Introduction

The existence of glueballs is among the fundamental predictions of QCD, but the experimental evidence is still in debate. In QCD calculations on the lattice in quenched approximation the lightest glueball is found to have quantum numbers $J^{PC} = 0^{++}$ and a mass in the region 1400-1800 MeV (for review, see [1]). The effect of this approximation is still being investigated. In an alternative approach based on QCD sum rules a gluonic state of lower mass around 1000 MeV is required as well [2].

The search for the lightest glueball should therefore concentrate on the mass region up to about 1800 MeV in the scalar sector. This search has to proceed in parallel with the identification of the low mass scalar $q\bar{q}$ nonet(s). The glueball candidate should fulfill some general properties, it should be produced in particular in a gluon rich environment and its decay (for the unmixed glueball) should be "flavour-blind". Then the scalar states to be identified as members of the $q\bar{q}$ nonet or glueball should be found from the list provided by the Particle Data Group[3]

I=0: $f_0(400\text{-}1200)$, $(\sigma(600)?)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)\ldots$
I=$\frac{1}{2}$: $(\kappa(900)?)$, $K_0^*(1430)$, $K^*(1950)\ldots$
I=1: $a_0(980)$, $a_0(1450)\ldots$

There are different scenarios for interpretation which include Scenario A:
A starting point is the lattice result, then a glueball with suitable mass is $f_0(1500)$ [4]. As this state does not obey all wanted properties one includes the nearby $f_0(1370)$ and $f_0(1710)$ and all three scalars mix with the glueball and two $q\bar{q}$ states (for review of this popular approach, see [5]). In this case the low mass states like $a_0(980)$ and $f_0(980)$, possibly also κ and σ, are considered as multiquark states which should not be included in the $q\bar{q}$ spectroscopy.
Scenario B:
One tries to identify the $q\bar{q}$ nonet first including the a_0 and f_0. In our approach [6,7] the $f_0(980)$ and $f_0(1500)$ are the isoscalars of the $q\bar{q}$ nonet with large mixing, very similar to the η, η' in the pseudoscalar sector. The nonet is completed with $a_0(980)$ and $K_0^*(1430)$. The σ and κ are not considered as genuine resonances. The remaining states called $f_0(400-1200)$ and $f_0(1370)$ ("red dragon") correspond to a single broad state which we suggest to be the lightest glueball. The same scalar states are chosen on the basis of a theoretical model in [8], except for the $a_0(980)$, the existence of a glueball is not accepted though [5]. A similar scheme with a broad state as glueball is considered in [9], albeit at a higher mass; in this scheme the $f_0(1370)$ is taken as $q\bar{q}$. A glueball around 1000 MeV which mixes with a nonstrange isoscalar is also obtained in the QCD sum rule approach [2].

In order to distinguish these possibilities it is of primary importance to verify the existence of the states in question and to determine their con-

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stituent structure. As relevant criterion for a resonant state to be included in spectroscopy we require the amplitude to describe a full circle in the complex plane ("Argand diagram"), possibly distorted by a smoothly varying background amplitude. This requires the verification of the appropriate phase motion of the amplitude through an analysis of angular distributions.

2. Is there a scalar $K\pi$ resonance $\kappa(900)$?

Important new information to this discussion has been provided by the FOCUS collaboration on the semileptonic decay $D^+ \to \mu^+\nu K^-\pi^+$ [10]. From the forward backward asymmetry in the $K\pi$ decay they conclude on the presence of an S-wave component in the mass region studied from 0.8 to 1.0 GeV with constant phase $\phi_S = 45^\circ$ interfering with a K^* Breit-Wigner resonance. Because of the Watson theorem this phase should equal the elastic $K\pi$ scattering phase. This has been determined through the study of $K^-p \to K^-\pi^+n$ by isolating the one-pion-exchange contribution [11]. Indeed, the two results closely agree, the elastic phase shift slowly rises from $\sim 35^\circ$ to $\sim 50^\circ$ in the mass range considered. An S-wave resonance $\kappa(900)$ with width around 400 MeV would lead to a phase variation of $\sim 50^\circ$ in this mass region apparently not observed by FOCUS. The elastic $K\pi$ amplitude in [11] has been parametrized by a superposition of the $K_0^*(1430)$ and a background as $S = T(K_0^*)e^{2i\delta_B} + T_B$ where the background phase rises slowly and reaches $\delta_B \sim 50^\circ$ at the K_0^*. This background we do not consider as evidence for an additional resonance to be included in spectroscopy (see also [13]).

A related process is the hadronic decay $D^+ \to K^-\pi^+\pi^-$ studied by the E791 Collaboration[14]. The Dalitz plot shows again the presence of the $K^*(890)$ and $K_0^*(1430)$. If the S wave is fitted with an energy independent background amplitude and phase factor multiplying K^* no satisfactory description is obtained. With an additional κ resonance at mass 798 MeV and width 410 MeV a better fit is obtained. Such a result appears to contradict the above FOCUS result with almost constant phase in the region 800-1000 MeV. We expect that a better fit can be obtained as well if the elastic $K\pi$ phase shifts are used, parametrized by a background phase and phase factor for the K_0^* both energy dependent as in [11].

As an additional check of the fit to the Dalitz plot we suggest comparing not only to the mass spectra with fine binning but also to the higher moments of the decay angular distribution, in particular the first moment $\langle Y_1^0\rangle \sim \langle \cos\theta\rangle$ where $\cos\theta$, for given $m^2(K^-\pi_1^+)$, is related to $m^2(K^-\pi_2^+)$ (see also [12]). These moments should reflect the angular distribution of the $K^-\pi_1^+$ channel but with a smooth backround from the resonances in the $K^-\pi_2^+$ channel. Inspection of the Dalitz plot suggests again a strong variation of the asymmetry $\langle\cos\theta\rangle$ over the $K^*(890)$ region. For the time being we see no compelling evidence for an additional $K\pi$ resonance below 1 GeV.

3. Is there a scalar $\pi\pi$ resonance $\sigma(600)$?

The elastic $\pi\pi$ phase shifts are by now rather well known and a unique solution is established up to $\sim$ 1400 MeV [15], similar to the old results [16]. If the rapid phase variation due to $f_0(980)$ is removed one finds a slowly moving phase passing 90° at around 1000 MeV and another more narrow structure presumably related to $f_0(1500)$. The behaviour of this phase shift may be parametrized by a Breit-Wigner resonance of 1 GeV mass with large width of at least 500 MeV [6]; if additional background is included the resonance position may shift to higher values around 1400 MeV [9] or lower values around 600 MeV [17]. The question may be asked whether in other reactions, with different background, a resonance around 600 MeV appears with a corresponding phase variation. Several such proposals have been put forward and we consider some of them in the following.

1. $J/\psi \to \omega\pi\pi$

There is a peak around 500 MeV in the $\pi\pi$ mass spectra which may be a signal from a σ Breit-Wigner resonance [18]. Then the interference term $\mathrm{Re}(SD^*)$ between the (almost real) D wave which is dominated by $f_2(1270)$ and the resonant S wave would change sign at the mass of the σ and so the angular distribution $d\sigma/d\Omega \sim$

$|S|^2 + 10(3\cos^2\vartheta - 1)\ \mathrm{Re}(SD^*) + \mathcal{O}(|D|^2)$ would vary accordingly with a sign change of the $\cos^2\vartheta$ term (from + to –). The data [18] do not show any sign change below 750 MeV and therefore there is no indication for a Breit Wigner resonance at 500 MeV.

2. Central $\pi\pi$ production in $pp \to p(\pi\pi)p$
The mass distribution of the pion pair in this double Pomeron dominated process peaks shortly above threshold $\sim$ 400 MeV [19] and has been related to the $\sigma(600)$ as well. However, again, there is no related phase variation of the S wave amplitude which should become visible from the $S-P$ or $S-D$ interference terms. In this process we understand the origin of the peak. We propose this process to be dominated at low masses by Pomeron Pomeron $\to \pi\pi$ through one pion exchange very much like $\gamma\gamma \to \pi\pi$, the latter process is discussed in [20]. Indeed there is a close similarity between these two processes: the $I=0$ component peaks below 400 MeV and the D-wave already near 500 MeV with 1/3 of intensity. As the pion pole is near the physical region the $\pi\pi$ angular distribution is very steep, steeper than in more typical interactions mediated by vector (ρ) exchange. Therefore one estimates that the D wave becomes important not at m_{f_2} but already at $m_{f_2} \times (m_\pi/m_\rho) \sim 0.3$ GeV. This mechanism also explains the low mass peak of the S wave without associated phase variation. The production of a broad state at 1000 MeV as in elastic $\pi\pi$ scattering is possible in addition either by rescattering or by direct formation as in $\gamma\gamma \to \pi\pi$ [20].

3. Decay $D^+ \to \pi^-\pi^+\pi^+$
The $\pi^+\pi^-$ mass spectrum presented by the E791 Collaboration [21] shows three prominent peaks, one just above $\pi\pi$ threshold, one related to ρ and one to $f_0(980)$. Only fits including a light σ particle have been found successful according to their analysis. In analogy to the decay $D^+ \to K^-\pi^+\pi^+$ discussed above we would expect the low mass region to be governed by the elastic $\pi\pi$ scattering phase without additional resonance contributions. This should apply strictly to the corresponding semileptonic decay $D^+ \to \pi^-\pi^+\mu^+\nu$. As discussed above for the κ a resonant $\sigma(600)$ should yield a characteristic interference pattern in the projected $\langle\cos\theta\rangle$ moment which should be analysed. For the moment we consider the question of the $\sigma(600)$ in this process as open.

In conclusion, the first two processes show peaks at low mass but definitely no resonant phase motion, for the latter process this question is not definitely answered. We do not discuss here other peaks related to $\sigma \to \pi\pi$ ($\psi' \to J/\psi\pi\pi$, $Y', Y'' \to Y\pi\pi$, $\tau \to \nu_\tau 3\pi$, $f_0(1370/1500) \to 4\pi$) which are all lacking a phase analysis. For the moment we suppose the $\pi\pi$ phase shifts in all these processes could behave as in elastic $\pi\pi$ scattering with a broad state around 1 GeV but no narrower state below 1 GeV.

4. Has $f_0(1500)$ a strong glueball component?

The main argument [6] against a strong glueball component in $f_0(1500)$ is the observed negative relative phase between the amplitudes

$$T(\pi\pi \to f_0 \to K\overline{K}) = -T(\pi\pi \to f_0 \to \eta\eta). \quad (1)$$

These amplitudes have been reconstructed from the measured $|S|, |D|$, their relative phase and the absolute phase of the D wave resonances. A similar behaviour of amplitudes (although with different overall phase) is also found in the fits by [22]. This constraint strongly restricts the possible admixture of a glueball component which would contribute with the same sign to all pseudoscalar particle pairs. In particular, among the six models listed in Table 4 of [5] which describe the $f_0(1500)$ as superposition of $u\bar{u} + d\bar{d}$, $s\bar{s}$ and glueball only two [23,24] yield a negative sign between the amplitudes (1) with a glueball amplitude of 0.22 and 0.01 resp. or a probability of less than 4% for the glueball component.

5. The candidate scalar glueball

Having constructed the low mass $q\bar{q}$ nonet with $f_0(980), f_0(1500), a_0(980)$ and $K^*(1430)$ [6,7] and not accepting σ and κ as genuine resonances below 1 GeV the states left in in our list at low mass are $f_0(400-1200)$ and $f_0(1370)$. We do not discuss here $f_0(1370)$, a full circle in the Argand diagram has not been established in our view [6,12], also there are problems with an inconsistency of branching ratios [5]. These two objects we consider as representing one single broad resonance as suggested in particular by elastic $\pi\pi$ scattering and this is our glueball candidate $gb(1000)$.

This state fulfils most standard requirements on glueballs:
1. central production in pp scattering;
2. decay of radially excited states ψ', Y', Y'' into the respective ground state and $\pi\pi$, this can only proceed through gluonic intermediate states;
3. Low energy $p\bar{p} \to 3\pi$;
4. $J/\psi \to \gamma\pi\pi$: no prominent signal is observed here up to now which is the only unfavourable aspect of our hypothesis;
5. Flavour properties: The decays of the glueball component $f_0(1370)$ favours a glueball over a non-strange $q\bar{q}$ assignment (see, for example, [25]);
6. Small coupling to $\gamma\gamma$, see our discussion [26];
7. t-channel analysis of elastic $\pi\pi$ scattering: The isoscalar exchange amplitude below 1 GeV cannot be saturated by $q\bar{q}$ resonances alone [26].

6. Conclusions

We found no definitive evidence for the low mass κ and σ Breit-Wigner resonances below 1 GeV, in particular, the semileptonic D decays speak against the κ; similar clarity on the σ could be obtained from semileptonic decays into $\pi\pi$. The $f_0(1500)$ can only have a small glueball component. The broad state $gb(1000)$ is a realistic glueball candidate. Our analysis is mainly phenomenological and driven by simplicity, this does not exclude more complex scenarios, such as a mixing between $f_0(980)$ and $gb(1000)$. Further experimental results would be helpful, for example the comparative study of quark and gluon jets in their respective fragmentation regions [27].

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